

Changes in the Pasterze and the Kleines Fleißkees glaciers, Austria, as Measured from the Ground and Space

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ABSTRACT

The tongue of the Pasterze Glacier in the eastern Alps of Austria receded more than 1152 m from 1880 to 2001. Landsat and Ikonos satellite data from 1976 to 2001, topographic maps beginning in 1893 and ground measurements were studied. Results show that though satellite images significantly underestimate the width of the Pasterze Glacier tongue due to the presence of morainal material on the surface, they provide an excellent way to measure the recession of the exposed-ice part of the glacier tongue. The rate of change of the terminus as determined using satellite data is found to compare well with ground measurements. Between 1976 and 2001, Landsat-derived measurements show a recession of the terminus of the Pasterze Glacier of 479 ± 113 m (at an average rate of 18.4 m a^{-1}) while measurements from the ground showed a recession of 428 m (at an average recession of 17.1 m a^{-1}). Ikonos satellite images from 2000 and 2001 reveal changes in the exposed ice part of the Pasterze tongue, and a decrease in area of the exposed ice part of the tongue of $22,096 \text{ m}^2$. GPS points and a ground survey of the glacier terminus in August 2001 were plotted on a 1-m resolution Ikonos image, and showed the actual terminus shape and location. The nearby Kleines Fleißkees glacier lost

30% of its area between 1984 and 2001, and the area of exposed ice increased by 0.44 km², according to Landsat satellite measurements. Recession of both the Pasterze and the Kleines Fleißkees corresponds generally to temperature and precipitation trends, especially increasing summer temperatures, as determined from meteorological data acquired from the Sonnblick Observatory, however the smaller the Kleines Fleißkees reacts more quickly to climate changes than does the Pasterze Glacier.

INTRODUCTION

Glaciers throughout the Northern Hemisphere have been losing mass. **Hölzle and others (2000)** showed net mass balance decreases in 32 glaciers in the Northern Hemisphere in ten different mountain ranges between 1980 and 1997, with the mean thickness change about -0.3 m a⁻¹. Globally, small glaciers have generally been receding on all continents with the exception of Antarctica, where the mass balance of the ice sheet is poorly known (**Dyurgerov, 2002**).

Glaciers of the European Alps are retreating in response to regional climatic change. There has been a general increase in average (May through September) temperature and a decrease in the number of days with snowfall between May and September since 1886 (**Böhm, 1986; Bayr and others, 1994 and Schöner and others, 2000**). Since about 1850, the total areal extent of glacierized areas in the European Alps has decreased by about 35%, while the volume of ice has decreased by about 50% (**Haeberli and Hoelzle, 1995; Haeberli and others, 2000**). The meltwater from the glaciers in the Alps is very important to the generation of power, and along with seasonal snow cover, the glaciers are the primary sources for such major rivers as the Rhine, Rhone, Po and Inn.

Glacier behavior in the Austrian Alps before 1850 is not well known, however there are several reports about maximum stages around 1600-1650, 1770-1780, 1815-1820 and 1850-1860. Knowledge is especially poor about periods when the glaciers were in retreat (e.g., see **Nesje and Dahl, 2000**). Glaciers receded until about 1910 with the most important maximum of the 20th century occurring around 1920; there was a second minor maximum around 1980. Most of the glaciers stopped advancing in the mid-1980s due to warm summers and reduced snowfall. In 1988, about 80 percent of the Austrian glaciers were in recession (**Rott, 1993**).

There are 925 glaciers with a total area of 542 km² in the Austrian Alps. Five are larger than 10 km²; the majority is smaller than 1 km² as determined from aerial photographs taken in 1969. The Pasterze Glacier is the largest in Austria with an area of 19.8 km² in 1969 (**Rott, 1993**).

The Pasterze Glacier (47° 6'N, 12° 42'E) flows from the Johannisberg (3463 m), and is located in the Hohe Tauern, part of the Alps that extends east of the area around the Rhine River (**Figure 1**). The highest peak in Austria, the Grossglockner (3798 m), is located to the southwest of the Pasterze and its hanging glaciers contribute some ice and morainal material to the Pasterze. Annual measurements of the Pasterze tongue were

started in 1880 and continue to the present, providing an excellent record of glacier recession (**Wakonigg, 1991; Österreichischer Alpenverein, 2001**). Between 1979 and 1989, the mean equilibrium-line altitude (ELA) of the glacier was 2880 m a.s.l. (**Zuo and Oerlemans, 1997**). Regional differences in the ELA are primarily related to the precipitation patterns and the aspect of the glaciers (**Rott, 1993**).

The Pasterze Glacier reached its maximum position of approximately the last 150 years in 1851 (**Zuo and Oerlemans, 1997**). The terminus of the Pasterze Glacier has retreated each year since the winter of exceptionally heavy snow in 1965-66, the total cumulative recession as measured on the ground being 579 m (**Wakonigg, 1991; Österreichischer Alpenverein, 2001**). Previous work showed that between 1984 and 1990, the terminus of the glacier receded at an average speed of $\sim 15 \text{ m a}^{-1}$ according to measurements made using Landsat Thematic Mapper (TM) data, for a total recession of 90 m (**Hall and others, 1992; Bayr and others, 1994**), while ground measurements showed a total recession of 102 m over that same period. Retreat and volume loss of the Pasterze Glacier tongue has intensified since 1982 (**Wakonigg and Tintor, 1999**). Since about 1982, during the period of negative mass balance, the specific net balance of glaciers in the Hohe Tauern is highly correlated with summer temperature and not with amount of winter precipitation (**Schöner and others 2000**).

The Kleines Fleißkees ($47^{\circ} 3' \text{N}$, $12^{\circ} 57' \text{E}$) is a small glacier that is located in the Goldberggroup, east of the Pasterze Glacier. The glacier flows from the Hohe Sonnblick (3105 m). The Kleines Fleißkees receded about 300 m between 1850 and 1870 and following that, was roughly stable until 1925 (**Auer and others, 2002**). Since then the glacier has receded nearly continuously with only one weak advance around 1980. **Bohm and others (1983)** showed that the ice volume increased between 1969 and 1979 and that the glacier gained 4.4 m in height during this time period. However, between 1979 and 1998 the glacier lost 14 m in height (**Auer and others, 2002**). **Bayr and others (1994)** showed an increase in the exposed ice area of the Kleines Fleißkees from 1984 to 1988, and ground measurements show a recession of 44 m.

In this paper, we discuss historical ice-front positions of the Pasterze, and provide measurements of ice-front position changes and glacier area, from ground, Landsat and Ikonos satellite data, and topographic maps. We also show changes in the nearby Kleines Fleißkees as measured using Landsat images.

Satellite Data

The Landsat Multispectral Scanner (MSS) was first launched in July 1972 on board the Landsat-1 satellite, providing images at a pixel resolution of approximately 80 m, in four spectral bands in the visible and near-infrared parts of the electromagnetic spectrum. The TM sensor was first carried on the Landsat-3 satellite in 1982. It provides 28.5-m pixel resolution images of the Earth's surface in seven spectral bands, ranging from the visible to the thermal-infrared part of the spectrum. The Enhanced Thematic Mapper plus (ETM+) <http://landsat.gsfc.nasa.gov/index.htm> was launched on the Landsat-7 satellite in

1999; it has eight discrete bands ranging from 0.45 to 12.5 μm ; the spatial resolution ranges from 15 m in the panchromatic band, to 60 m in the thermal-infrared band. All of the other bands have 30-m resolution. Each Landsat image covers an area 185 km on a side. A detailed comparison of the various band widths and other characteristics of the Landsat sensors may be found at: <http://landsat.gsfc.nasa.gov/project/Comparison.html>.

The Ikonos-1 satellite was launched on September 24, 1999, by Space Imaging. Ikonos simultaneously collects 4-m resolution multispectral data in blue, green, red and near-infrared bands located at: 0.45-0.52 μm , 0.52-0.60 μm , 0.63-0.69 μm , and 0.76-0.90 μm , respectively, and 1-m resolution panchromatic imagery (0.45-0.90 μm). The Ikonos images cover an area that is nominally 11 km on a side.

Topographic maps

Topographic maps were used to measure the areal extent of the Pasterze Glacier over approximately the last century, and to compare the earlier terminus positions with more recent terminus positions derived from satellite imagery. The oldest map, dated 1893, shows the greatest areal extent of the Pasterze tongue (**Spezialkarte von Österreich - Ungarn, 1893**). Another map showing the 1928 "Gletscherstand" (glacier position) was also used (**Deutscher und Österreichischer Alpenverein, 1928**). More recently, Austrian Alpine Club maps were employed to study the areal extent of the terminus (**Österreichischer Alpenverein, 1982 & 1992**). The Austrian Alpine Club maps are updated regularly and sometimes only the Gletscherstand are updated. The date of the Pasterze Gletscherstand is given on the maps, and this date is different from the publication date of the map. The 1982 map shows the 1965 Gletscherstand, and the 1992 map shows the 1985 Gletscherstand.

METHODOLOGY

Landsat scenes from 1976, 1984, 1986, 1988, 1990, 1992, 2000 and 2001 and Ikonos scenes from 2000 and 2001 have been studied (**Table 1**). We also obtained other Landsat scenes (from 1981 and 1999), but these were not used for detailed analysis due to either cloudcover or cloud shadows obscuring the glacier terminus.

All of the satellite images listed in **Table 1** were registered digitally to the 1984 Landsat TM scene (which is used as the "base") with a pixel resolution of 28.5 m. By registering the scenes to a common base, it is possible to measure changes of the terminus position and other features of the glacier between years. To register scenes or maps, about 100 tie points, points in common between the 1984 and the other images, were determined. A second-order polynomial was used to warp each image or map to the 1984 TM base image. In addition, the September 27, 2000, Ikonos image was registered to the October 3, 2001, Ikonos image to enable a detailed analysis of glacier change between 2000 and 2001.

To improve the contrast between the glacier ice and surrounding areas, a false-color composite image was used for the 1976 scene using MSS bands 4 (0.8-0.11 μm), 2 (0.63-0.76 μm) and 1 (0.45-0.52 μm). It was found that good contrast between the Pasterze Glacier tongue and the surrounding terrain was achieved using TM or ETM+ band 5 (1.55 – 1.75 μm) which is a short-wave infrared band, and thus band 5 imagery was used to measure the position of the glacier tongue when TM or ETM+ images were available. (The short-wave infrared band was not available on the MSS sensor.)

Once registered to a common base, changes in the terminus position of the Pasterze Glacier could be measured digitally. This technique was also used to measure the glacier terminus position change from 1893-2001. Changes in the areal extent and surficial conditions of the Kleines Fleißkees were also measured.

In this paper, we also show the temperature and precipitation data from the Sonnblick Observatory (SBO, 3105 m) which is located about 15 km east of the tongue of the Pasterze on the top of Hohe Sonnblick. The proximity of the Pasterze Glacier to Hohe Sonnblick offers the opportunity to complement the satellite-derived glacier measurements with a description of climate variability from meteorological data acquired at SBO where climate data have been recorded since in 1887.

RESULTS OF THE PASTERZE GLACIER STUDY

The recession of the Pasterze Glacier tongue from 1893 to 2001 is depicted in **Figure 2A**, and from 1976 to 2001 in **Figure 2B**. **Figure 2A** is a color composite (bands 5, 4, 2) of the August 26, 2001 ETM+ image showing the glacier tongue. The recession from 1893 to 2001, measured using map and satellite data, is difficult to compare with the ground measurements because the recession varies depending at which point on the terminus is selected. Also, the retreat of the tongue did not go in a straight line and ground measurements are made nearly every year as seen in **Figure 3**. Our measurements show a recession of 1300 to 1800 m, depending on what point is selected as the terminus position using the 1893 map. Ground measurements (the summation of individual years of measurements) show a recession of ~1074 m (**Wakonigg, 1991; Österreichischer Alpenverein, 1999 and 2001**). Some of the difference between the ground and satellite measurements can be explained by the fact that the terminus is debris-covered and thus not visible on the 2001 ETM+; additionally, there are seven missing years of ground measurements.

The 1928 position of the glacier tongue was also studied (**Deutscher und Österreichischer Alpenverein, 1928**) and the tongue was found to be narrower, on the eastern side of the glacier, and shorter than it was in 1893 by 161 m according to the ground measurements.

Recession of the Pasterze Glacier terminus and narrowing of the exposed parts of its tongue were also measured using Landsat data from the summers of 1976 to 2001 (**Figure 2B**). The total recession, as measured from 1976 to 2001 at the farthest reach of the exposed ice part of the tongue, is 479.0 ± 113 m (or an average rate of ~ 19.2 m a^{-1}),

while ground measurements show a recession of 428.5 m ($\sim 17.1 \text{ m a}^{-1}$). A $\pm 40 \text{ m}$ uncertainty of the satellite measurement is derived using the estimated one pixel (28.5 m) error in terminus position between each TM or ETM+ image, and the uncertainty is greater ($\pm 113 \text{ m}$) when the 1976 MSS image, with its 80-m resolution, is used. **Table 2** shows the position of the glacier-terminus change from topographic maps and satellite data as well as from the ground measurements. Ground measurements of the terminus changes, started in 1880, are shown in **Figure 3**.

Wakonigg and Tintor (1999) showed that the recession of the Pasterze terminus has intensified since 1982. The average rate of recession for the entire period of record (1880 to 2001) is 9.5 m a^{-1} according to the ground data. Between 1880 and 1981 the average rate of recession is 8.0 m a^{-1} , while it is 18.1 m a^{-1} from 1982 to 2001.

Even on the ground, it can be difficult to tell the exact position of the terminus of the Pasterze Glacier because of the obscuring debris. Field measurements in August of 2001 indicate that the thickness of the morainal material covering part of the Pasterze tongue varies from a few centimeters to about a meter. As the glacier recedes, debris collects on the surface of the ice. Inspection of the digital numbers (DNs) from the Landsat data (using all seven bands) shows that data from the TM sensor cannot distinguish glacier ice below surface debris of the glacier tongue. In **Figure 4A**, the 1984 image is shown with a solid yellow line outlining the visible part of the tongue. The dotted line in the western part of the tongue shows the actual position of the tongue as determined from a 1992 topographic map on which the 1985 Gletscherstand is shown (**Österreichischer Alpenverein, 1992**). In **Figure 4B**, a transect across the image at the red line (northeast to southwest) in **4A**, shows that in the debris-covered part of the terminus (the southwestern part of the terminus), the DN's cannot be used to distinguish the ice below.

The August 2001 boundary of the lower part of the Pasterze glacier tongue was verified using global positioning system (GPS) measurements made at the terminus of the Pasterze on August 23, 2001. The GPS points are shown on the October 3, 2001 Ikonos image from the panchromatic band which provides 1-m resolution (**Figure 5**). The accuracy for each GPS point is shown in **Table 3**. The lines connecting the points represent our estimate of the glacier boundary based on field work by one of the authors (K.J.B.). Point "R" represents a point at which the supra-glacial stream is located. The supra-glacial stream is the approximate boundary between the till-covered and till-free parts of the tongue. Point "L" represents the farthest extent of the glacier.

Comparison of the 4-m resolution false-color Ikonos images from September 27, 2000 and October 3, 2001, reveals a decrease in area of the terminus of $22,096 \text{ m}^2$ as seen in **Figure 6**. This quantifies the field observations whereby a significant change was observed from the summers of 2000 and 2001.

RESULTS OF THE KLEINES FLEIBKEES STUDY

Full-resolution false-color TM (1984 and 1992) and ETM+ (2001) images of the Kleines Fleißkees and the adjacent Vogelmaier Ochsenkar Kees glaciers are shown in **Figure 7**. Using a false-color combination of bands 5, 4, 2, the exposed ice area was measured. If the exposed ice area is the same as the ice facies (**Benson, 1962**), then the accumulation area ratio (AAR) (**Paterson, 1994**) can be calculated for each year shown. (However, it is possible that a new summer snow cover, if only temporary, was present on any of the satellite images thus the exposed ice area may not exactly coincide with the ice facies.)

The Kleines Fleißkees experienced major shrinkage between 1984 and 2001 as shown in **Figure 8 and Table 4**. Satellite measurements from 1984 to 2001 show that the glacier lost ~30% of its area from 1984 to 2001; the area of exposed ice increased by 0.44 km² over this period. Bare ice comprised nearly 61% of the total area of the glacier in August 2001 .

THE IMPACT OF REGIONAL CLIMATE CHANGE ON GLACIER VARIABILITY

The observed changes of front positions of both glacier sites can be explained by the climate data from SBO (**Schöner and others, 2000; Auer and others, 2001**). Although changes of the front position of a glacier result from both mass balance variability (from weather trends) and individual flow dynamics of a glacier, it is out of the scope of this paper to include the flow dynamics of Pasterze and Kleines Fleißkees.

Changes of specific net balance of a glacier can be explained by changes of summer air temperature and amount of winter precipitation (falling as snow). However, this is based on the knowledge that there is a particularly high correlation between summer air temperature and shortwave radiation balance. This is especially true for high elevation climate stations such as SBO (**Schöner and others, 2000**). In **Figure 9**, a time series of annually-averaged summer air temperature (May to September, since 1887) and winter precipitation (October to April, since 1927), is shown along with 30 years of low-pass filtered values. There is a decrease in summer temperature between about 1910 and 1920, and this is most likely responsible for a general glacier advance in the Austrian Alps around this time. A glacier recession in the Austrian Alps after 1920 was due to increasing summer temperature with a maximum around 1950. The glacier maximum around 1980 was caused by reduced summer temperatures and increased winter precipitation in the 1960s and 1970s. These climatic trends are more obviously translated into glacier changes in the smaller Kleines Fleißkees (**Figure 8**) as compared to the Pasterze Glacier (**Figure 3**), with its longer response time. A detailed discussion of climate variability and glacier recession in the Austrian eastern Alps can be found in **Schöner and others (2000)**.

In addition to the regional climate variability, glacier mass balance is also influenced by local climate effects, for example, the katabatic winds for large valley glaciers. **Van den**

Broeke (1997) showed that strong and very persistent gravity (katabatic) winds on the Pasterze Glacier tongue enhance the melting of the ice and snow on the tongue.

DISCUSSION

It is sometimes impossible to measure, accurately, the position of a glacier terminus from space. This was demonstrated in **Williams and others (1997)** in a study of glacier changes on Vatnajökull, Iceland, using Landsat data. When a glacier is in recession, debris may collect on the surface of part or all of the glacier tongue and the glacier will have a spectral reflectance similar to the surrounding moraine. This can make the exact terminus difficult to locate, especially from space. Advancing glaciers, and other receding glaciers, such as tidewater glaciers, are generally easier to measure from space (**Hall and others, 1995**). However, even on receding glaciers with copious amounts of surficial morainal material such as the Pasterze Glacier, excellent results are often obtained by monitoring glacier changes from space. On the ground, the terminus position can usually be determined by digging into the top layers of the debris but this is a very labor-intensive activity. If ice is found, then that may represent the position of the terminus, although stagnant ice, unconnected to the glacier tongue may further confuse the determination of the terminus.

A glacier tongue can transport a large amount of debris, and when the glacier recedes and melts down, the sediment accumulates on the top and sides of the tongue. Field measurements show that the Pasterze Glacier tongue has been consistently much larger than it appears in the satellite imagery because part of the tongue is covered with a layer of debris. On the west side of the Pasterze Glacier tongue, the terminus is covered by morainal material that has a variable thickness while the east part is almost free of obscuring debris.

Satellite measurements of changes in the exposed ice part of the Pasterze tongue correspond to changes of the entire terminus as measured on the ground. Changes in terminus position measured using satellite data may overestimate glacier recession because only the exposed-ice area is visible from space, the rest of the terminus having been covered by morainal material. But as long as the debris-covered part of the terminus is attached, then it is still considered part of the tongue. (Blocks of ice can become detached and stagnant and they are no longer part of the glacier.) Thus the satellite data are excellent indicators of glacier recession if measured over a period of time. Periodic ground measurements are important in order to "calibrate" the satellite measurements.

Climate data from SBO show that the average summer temperature increased by 1.7°C from 1910 to 2001. This general warming resulted from two major warming periods, the first between 1910 and about 1950, and the second between about 1970 and 2001. There was a period of general cooling between about 1950 and 1970. Long-term precipitation data from SBO show a large increase of winter precipitation in the 1960s. This helps to

explain periods of general glacier advance in 1960s and 1970s. A decrease in winter precipitation helps to explain glacier recession in the 1980s.

For the Pasterze Glacier, the more positive mass balances resulted only in a roughly stable length of the tongue around 1920, and in a slightly reduced retreat in the 1970s. This may be because the response time, on the order of 50-70 years (**Johannesson and others, 1989**), is long enough that the years with positive mass balance did not result in an advance of the glacier tongue during the 20th century. Changes in the smaller Kleines Fleißkees more closely tracked the climate trends.

As shown by **Oerlemans and Fortuin (1992)**, even a significant increase in precipitation cannot compensate for increased melting if the summer temperatures are high. High summer temperatures have been determined to be the most important factor in determining the negative mass balance of the Pasterze Glacier.

CONCLUSIONS

From 1976-2001, ground measurements show that the Pasterze Glacier tongue receded ~ 428 m (or 17.1 m a^{-1} on average), while measurements using Landsat TM and ETM+ data show a recession of 479 ± 40 m (or 19.1 m a^{-1}). The ground measurements are more accurate than are the satellite measurements, and though the satellite measurements from 1976 to 2001 tend to overestimate the actual recession during that period, they give an excellent representation of the exposed ice areal extent of the terminus and its changes.

Even when only about one year intervened between Ikonos images (from September 27, 2000 to October 3, 2001), deterioration of the Pasterze Glacier tongue is evident. A decrease in area of $22,096 \text{ m}^2$ was measured using 4-m resolution imagery.

The Landsat database, beginning in 1972, enables decadal-scale glacier changes to be measured with increasing detail, and is an important resource for measuring glacier changes and correlating those changes with regional climate changes in most glacierized areas on the Earth. Sensors like the Ikonos provide even better resolution for studying detailed changes between years. Fine-resolution imagery is excellent for detailed mapping of the glacier tongue. The value of these high-resolution data for monitoring detailed changes in glaciers will increase as more years of the data become available.

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REFERENCES

- Auer I. R. Böhm, W. Schöner, 2001, Austrian long-term climate 1767-2000 - multiple instrumental climate time series from central Europe, *Österreichische Beiträge zur Meteorologie und Geophysik*, Heft 25, 147 pages.
- Auer I., R. Böhm, M. Leymüller, W. Schöner, 2002, Das Klima des Sonnblicks - Klimaatlas und Klimatographie der GAW-Station Sonnblick einschließlich der umgebenden Gebirgsregion, *Österreichische Beiträge zur Meteorologie und Geophysik*, Heft 29, (in press)
- Bayr, K.J., D.K. Hall and W.M. Kovalick, 1994: Observations on glaciers in the eastern Austrian Alps using satellite data, *International Journal of Remote Sensing*, 15(9):1733-1752.
- Benson, C.S., Stratigraphic studies in the snow and firn of the Greenland ice sheet, Snow, Ice and Permafrost Research Establishment (now U.S. Army Cold Regions Research and Engineering Laboratory), Research Report 70 (reprinted and updated in 1996), 93 p. + appendices.
- Böhm, R., N. Hammer and J. Stoble, 1983: Analyse der Veraenderungen von drei benachbarten alpinen Gletschern in der Goldberggruppe der Hohen Tauern seit 1930, *Mitteilungen der Oesterreichischen Geographischen Gesellschaft*, 125:116-151.
- Böhm, R., 1986: Der Sonnblick, *Oesterreichischer Bundesverlag*, Vienna, 222 p.
- Deutscher und Oesterreichischer Alpenverein, 1928: Karte der Glocknergruppe. 1:25,000.
- Dyurgerov, M., 2002: Glacier mass balance and regime: data of measurements and analysis, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, Occasional Paper No. 55, 268 p.
- Haeberli, W., M. Hoelzle, 1995: Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, *Annals of Glaciology*, 21:206-212.
- Haeberli, W., J. Cihlar and R.G. Barry, 2000: Glacier monitoring within the Global climate observing system, *Annals of Glaciology*, 31:241-246.
- Hall, D.K., R.S. Williams, Jr. and K.J. Bayr, 1992: Glacier recession in Iceland and Austria as observed from space, *EOS*, 73(12):129, 135 and 141.
- Hall, D.K., C.S. Benson and W.O. Field, 1995: Changes of glaciers in Glacier Bay, Alaska, using ground and satellite measurements, *Physical Geography*, 16(1):27-41.

Hölzle, M., Dischl, M., and Frauenfelder, R., 2000: Weltweite Gletscherbeobachtung als Indikator der globalen Klimaänderung. Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich 145/1: 5-12

Johannesson T. Raymond C., E. Waddington, 1989, Time scale for adjustment of glaciers to changes in mass balance, *Journal of Glaciology*, 35(121):355-369

Nesje A. and S.V. Dahl, 2000, *Glaciers and Environmental Change, Key Issues in Environmental Change*, Arnold, UK, 203 pages.

Orelemans, J. and J.P.F. Fortuin, 1992: Sensitivity of glaciers and small ice caps to greenhouse warming, *Science*, 258:115-117.

Österreichischer Alpenverein, 1982 & 1992: Alpenvereinskarte Grossglocknergruppe, 1:25,000, Nr.40.

Österreichischer Alpenverein, 1999 & 2001
<http://www.alpenverein.at/gletscherbericht.htm>.

Paterson, W.S.B., 1994, *The Physics of Glaciers*, 3rd edition, Pergamon, 480 p.

Rott, H., 1993: *The Glaciers of Europe – Glaciers of the Alps. The Austrian Alps*, R.S. Williams, Jr. and J.G. Ferrigno, eds., U.S. Geological Survey Professional Paper 1386-E: E6-E13.

Schöner, W., I. Auer and R. Böhm, 2000: Climate variability and glacier reaction in the Austrian eastern Alps, *Annals of Glaciology*, 31:31-38.

Spezialkarte von Österreich-Ungarn, 1893: Grosz-Glockner, Zone 17, Col. VII, 1:75,000.

Van den Broeke, 1997: Structure and diurnal variation of the atmospheric boundary layer over a mid-latitude glacier in summer, *Boundary Layer Meteorology*, 83:183-205.

Wakonigg, Herwig, 1991: Die Nachmessungen an der Pasterze von 1879 bis 1990, Arb. Geogr. Inst., Graz, 30: 271-307.

Wakinogg, H. and W. Tintor, 1999: Zum Massenumsatz der Pasterzenzunge zwischen 1979 und 1994, *Wissenschaftliche Mitteilungen aus dem Nationalpark Hohe Tauern*, Bd.5:193-203.

Williams, R.S., Jr., D.K. Hall, O. Sigurdsson and J.Y.L. Chien, 1997: Comparison of satellite-derived with ground-based measurements of the fluctuations of the margins of Vatnajökull, Iceland, 1973-92, *Journal of Glaciology*, 24:72-80.

Zou, Z. and J. Oerlemans, 1997: Numerical modelling of the historic front variation and the future behaviour of the Pasterze Glacier, Austria, *Annals of Glaciology*, 24:234-241.

Table 1. Landsat (MSS, TM or ETM+) and Ikonos data used in this paper.

Sensor	Date	Path/Row	Scene i.d. #
MSS	August 26, 1976	206/27	8D20602776239
TM	August 3, 1984	192/27	LT5192027008421610
TM	August 9, 1986	192/27	LT5192027008622110
TM	August 6, 1988	192/27	LT4192027008821910
TM	August 4, 1990	192/27	LT5192027009021610
TM	August 1, 1992	192/27	LT4192027009221410
ETM+	July 22, 2000	192/27	LE7192027000020450
Ikonos	September 27, 2000	N/A	2000092709463890000011622536
ETM+	August 26, 2001	192/27	LE7192027000123850
Ikonos	October 3, 2001	N/A	2000011178400THC

Table 2. Average recession (m) of Pasterze Glacier terminus using ground data (1883-2001) and satellite data (1976-2001).

Years of measurements	Total recession (m) from satellite measurements and average rate of recession (m a^{-1}) in parenthesis	Total recession (m) from ground measurements and average rate of recession (m a^{-1}) in parenthesis
1880 – 1975	N/A	-724.3* (7.6)
1976 – 1984	-145.3 \pm 113 (18.1)	-127.7 \pm 113 (16.0)
1985 – 1992	-142.5 \pm 40 (17.8)	-134.0 \pm 40 (19.1)
1993 – 2001	-191.2 \pm 40 (21.2)	-166.1 \pm 40 (20.8)

*Uncertainty unknown

Table 3. Accuracy of GPS points acquired on August 23, 2001, on the Pasterze Glacier tongue.

Point	Accuracy (m)
A	10
B	11
C	7
D	6
E	5
F	N/A
G	6
H	8
I	8
J	8
K	9
L	11
M	21
N	13
O	5
P	11
Q	3
R	9

Table 4. Changes in the total areal extent, and area of exposed ice of the Kleines Fleißkees, as measured using Landsat data.

Date	Total area (km ²)	Exposed ice area (km ²)	% of total
August 3, 1984	1.45	0.18	12.4
August 1, 1992	1.17	0.42	36.0
August 26, 2001	1.02	0.62	60.8

FIGURES

Figure 1. Location map showing Austria; the circle in southwestern Austria shows the approximate location of the Hohe Tauern.

Figure 2A. Representation of the 1893 position of the Pasterze Glacier tongue from the map (**Spezialkarte von Österreich Ungarn, 1893**) relative to the 2001 position on the August 26, 2001, Landsat ETM+ image, false-color composite.

Figure 2B. ETM+ band 5 (1.55-1.75 μm) image from August 23, 2002, showing changes in the position of the exposed ice part of the Pasterze Glacier tongue from 1976 (yellow line), to 2001 (red line).

Figure 3. Recession of the Pasterze Glacier tongue as measured on the ground from 1880 - 2001 (**Wakonigg, 1991; Österreichischer Alpenverein, 1982 and 1992**). The red lines show the average recession (in m a^{-1}) measured from Landsat data.

Figure 4A. Landsat TM color composite image, August 3, 1984, showing the satellite-derived position of the Pasterze Glacier tongue (solid yellow line), and the extent of the tongue from the map (dotted yellow line); the red line represents the transect (NE to SW) shown in **Figure 4B**.

Figure 4B. Digital counts from the Landsat TM bands across the Pasterze Glacier tongue as measured from the solid red line in **Figure 4A**.

Figure 5. The base image is the October 3, 2001 Ikonos image (panchromatic band (0.45-0.9 μm)). Global positioning system (GPS) measurements from August 23, 2001 are shown as blue points. The red line that connects the points delimits the glacier terminus. Point "R" (in the center of the glacier), represents the location of the supra-glacial stream that divides the till-covered from the exposed-ice parts of the Pasterze Glacier terminus.

Figure 6A. 4-m resolution Ikonos false-color image from October 3, 2001 showing the tongue of the Pasterze Glacier; the red box shows the area covered in **Figure 6B**.

Figure 6B. Zoomed Ikonos 4-m resolution image of the Pasterze Glacier terminus from October 3, 2001; the yellow line is a trace of the position of the exposed ice area of the terminus as measured from the September 27, 2000 Ikonos image; the blue line shows the extent of the exposed ice area on the 2001 image.

Figure 7. Landsat images at full resolution (28.5 m) of the Kleines Fleißkees and Vogelmaier Ochsenkar Kees from 1984, 1992 and 2001. The classified sub images of the Kleines Fleißkees superimposed on a false-color composite image (TM or ETM+ bands 5, 4, 2) are adjacent to the corresponding Landsat image.

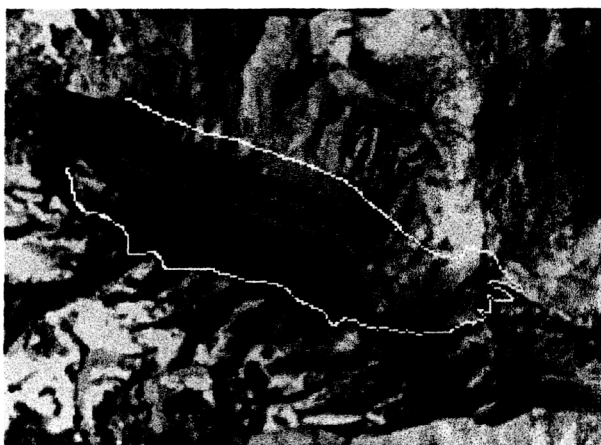
Figure 8. Recession of the Kleines Fleißkees as measured on the ground from 1850 - 2001 (**Auer and others, 2002**).

Figure 9A. Average annual and average spring/summer (May through September) temperature (in °C) from the Sonnblick Observatory, Austria, 1887-2000.

Figure 9B. Annual total and spring/summer total (May through September) precipitation (in cm) from the Sonnblick Observatory, Austria, 1927-2000 (**Schöner et al., 2000**).



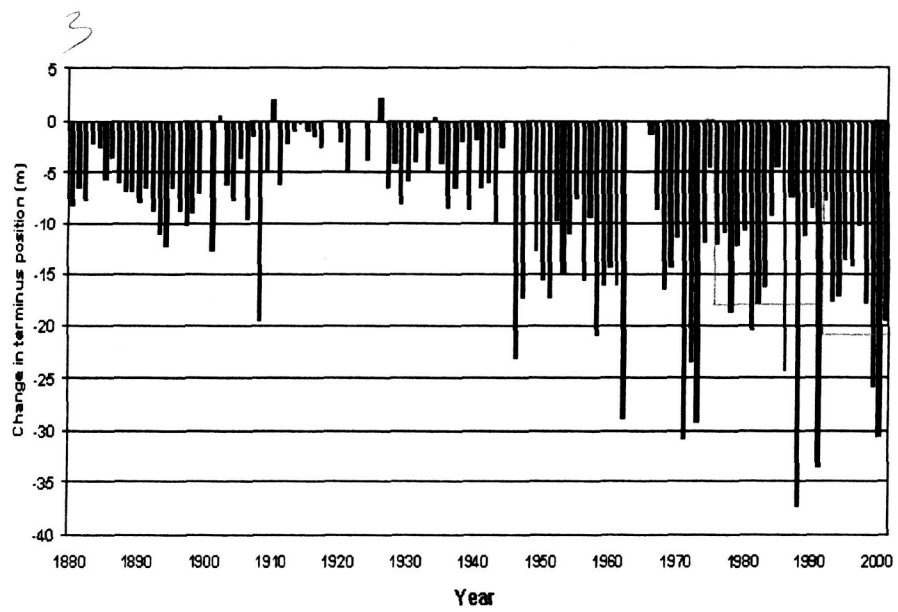
2A



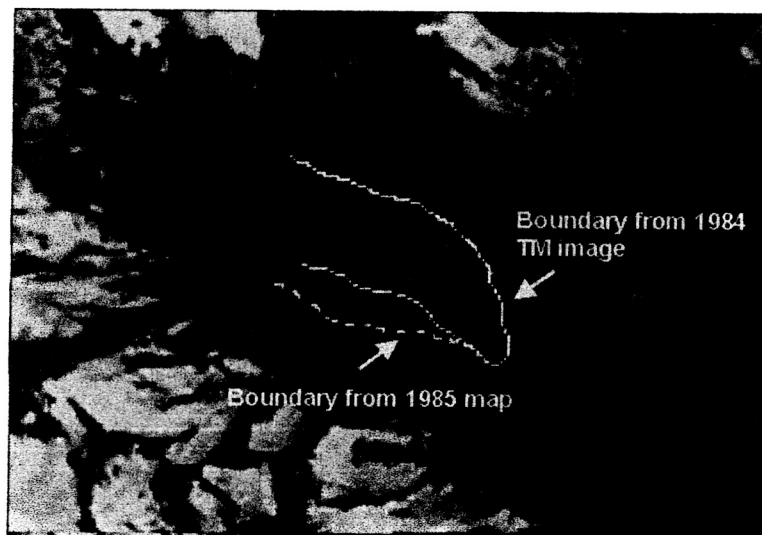
2B



0 1 2 3 km

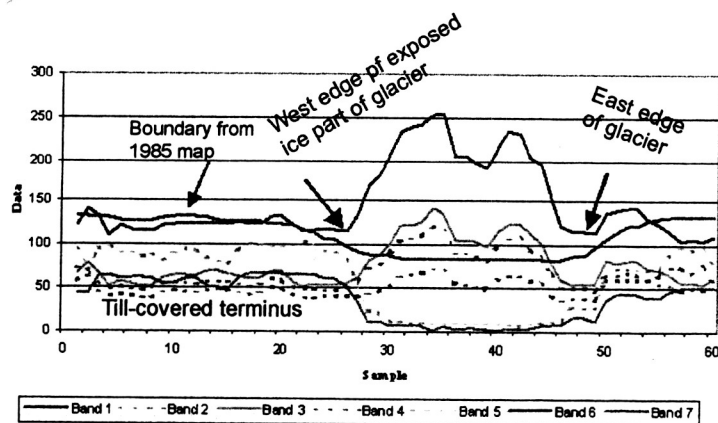


41A



0 1 2 3 km

4B





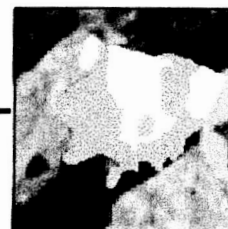
6A





6B

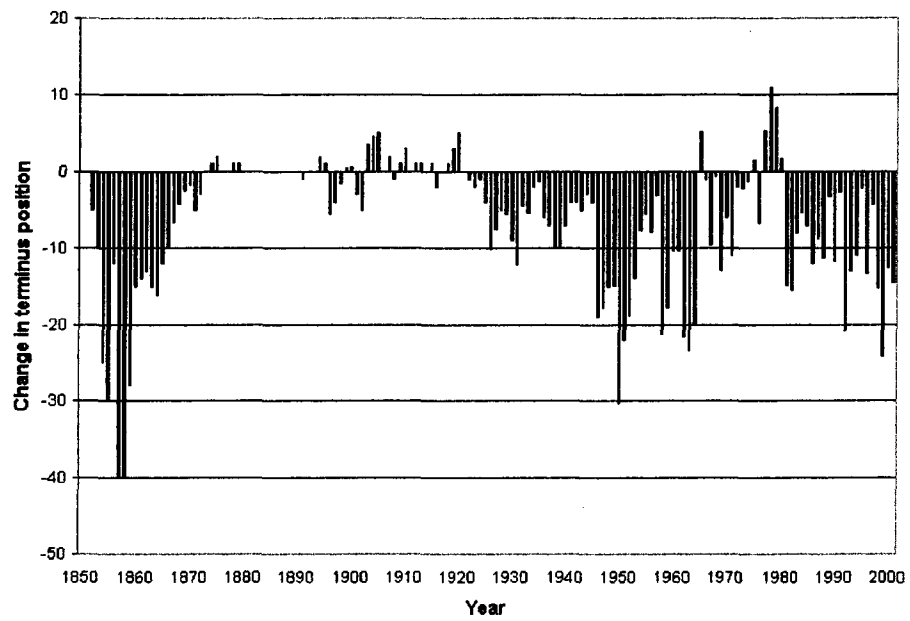


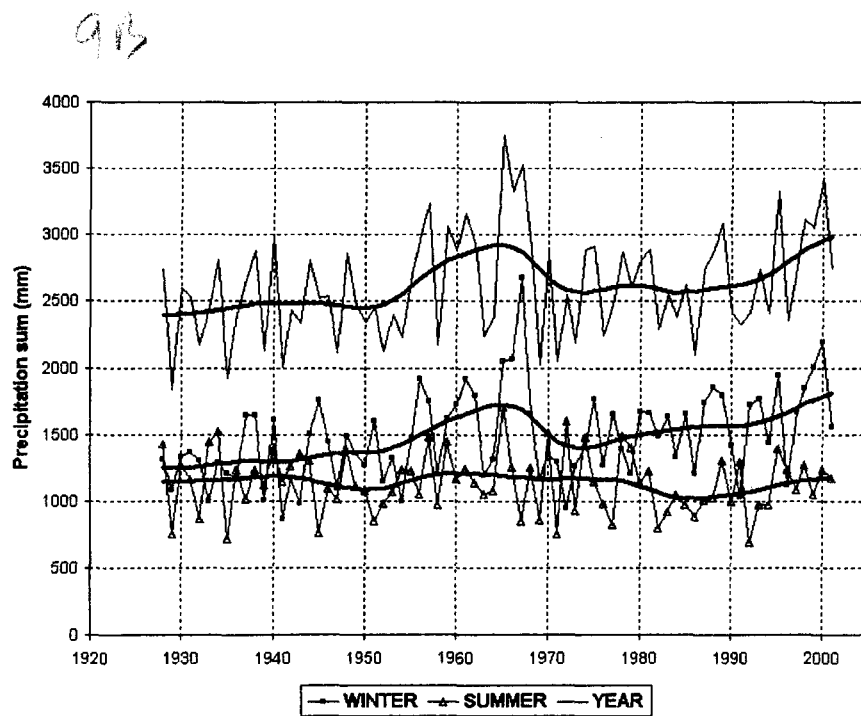
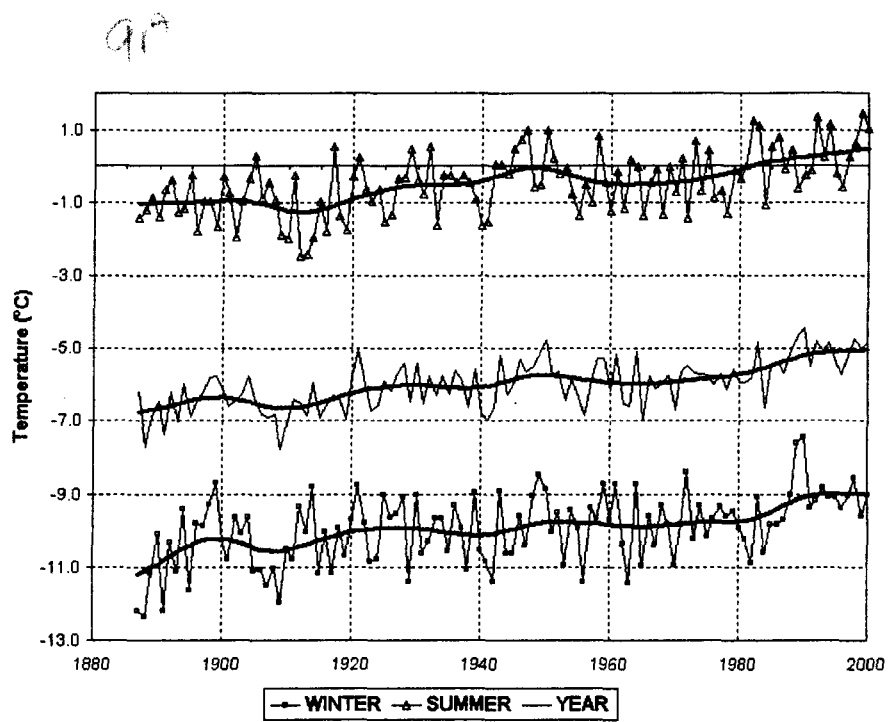
7



0 1 2 3 km

-  Area of exposed ice
-  Area of snow- or firn-covered ice





Changes in the Pasterze and the Kleines Fleißkees glaciers, Austria, as Measured from the Ground and Space

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Popular Summary

The Pasterze Glacier in the eastern Alps of Austria has receded more than 1152 m from 1880 to 2001 in response to a climate warming. Landsat and Ikonos satellite data from 1976 to 2001, topographic maps beginning in 1893 and ground measurements were studied. Results show that satellite images provide an excellent way to measure the recession of the exposed-ice part of the glacier tongue. The rate of change of the terminus as determined using Landsat data is found to compare well with ground measurements. Ikonos satellite images from 2000 and 2001 reveal changes in the exposed ice part of the Pasterze tongue, and a decrease in area of the exposed ice part of the tongue of 22,096 m². The nearby Kleines Fleißkees glacier lost 30% of its area between 1984 and 2001, and the area of exposed ice increased by 0.44 km², according to Landsat satellite measurements. Recession of both the Pasterze and the Kleines Fleißkees corresponds generally to temperature and precipitation trends, especially increasing summer temperatures, as determined from meteorological data acquired from the Sonnblick Observatory, however the smaller the Kleines Fleißkees reacts more quickly to climate changes than does the Pasterze Glacier.

Temperatures measured from the Sonnblick Observatory reveal a clear pattern of regional warming. In short, we can measure changes in small glaciers from space even in areas where no temperature measurements exist. The small glaciers, found on all continents except Australia, are sensitive indicators of climate change and can be measured for changes even when meteorological data are not available.